2017-12

Episodic changes in lagoon water levels due to ephemeral river breaching and closure events

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http://hdl.handle.net/10945/56801

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

EPISODIC CHANGES IN LAGOON WATER LEVELS DUE TO EPHEMERAL RIVER BREACHING AND CLOSURE EVENTS

by

Jeffrey D. Scooler

December 2017

Thesis Advisor: Mara Orescanin
Second Reader: Jamie MacMahan

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704–0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** December 2017	**3. REPORT TYPE AND DATES COVERED** Master's thesis	
4. TITLE AND SUBTITLE EPISODIC CHANGES IN LAGOON WATER LEVELS DUE TO EPHEMERAL RIVER BREACHING AND CLOSURE EVENTS			**5. FUNDING NUMBERS**
6. AUTHOR(S) Jeffrey D. Scooler			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

Carmel River, near Carmel, CA, is a seasonally open, ephemeral river that has a basin of 660 km^2. During the dry summer months, the barrier beach is built across the river mouth, limiting water exchange. Precipitation during the winter months increases the discharge within the river until water levels are sufficiently high to breach the barrier beach. Observations during the 2016–2017 winter allow for a dynamic balance between discharge, wave forcing, and tidal exchange that led to several distinct breaching and closure events. The initial breach occurred after the first major precipitation event but was insufficient to keep the river open, owing to wave forcing at the mouth. Wave penetration into the estuary through overtopping and upstream propagation is routinely observed during this stage. In order to evaluate the conditions responsible for the intermittent opening and closing of the inlet, water level, wave, tidal and discharge data were collected. With this data, a momentum balance was developed to estimate the ocean forcing (tides and waves) as compared to discharge. It is hypothesized that a critical discharge is required to maintain an open river mouth, depending on offshore wave forcing.

14. SUBJECT TERMS Carmel River, overtopping, breaching, closure			**15. NUMBER OF PAGES** 65
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT** UU

NSN 7540–01-280-5500

Standard Form 298 (Rev. 2–89)
Prescribed by ANSI Std. 239–18

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EPISODIC CHANGES IN LAGOON WATER LEVELS DUE TO EPHEMERAL RIVER BREACHING AND CLOSURE EVENTS

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Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN METEOROLOGY
AND PHYSICAL OCEANOGRAPHY**

from the

**NAVAL POSTGRADUATE SCHOOL
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Carmel River, near Carmel, CA, is a seasonally open, ephemeral river that has a basin of 660 km^2. During the dry summer months, the barrier beach is built across the river mouth, limiting water exchange. Precipitation during the winter months increases the discharge within the river until water levels are sufficiently high to breach the barrier beach. Observations during the 2016–2017 winter allow for a dynamic balance between discharge, wave forcing, and tidal exchange that led to several distinct breaching and closure events. The initial breach occurred after the first major precipitation event but was insufficient to keep the river open, owing to wave forcing at the mouth. Wave penetration into the estuary through overtopping and upstream propagation is routinely observed during this stage. In order to evaluate the conditions responsible for the intermittent opening and closing of the inlet, water level, wave, tidal and discharge data were collected. With this data, a momentum balance was developed to estimate the ocean forcing (tides and waves) as compared to discharge. It is hypothesized that a critical discharge is required to maintain an open river mouth, depending on offshore wave forcing.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

CDIP	Coastal Data Information Program
CTD	Conductivity/Temperature/Salinity Sensor
MPWMD	Monterey Peninsula Water Management District
NDBC	National Data Buoy Center
PRESS	Pressure Sensor
RBR	RBR Solo Pressure Sensor
TCM	Tilt Current Meter
WL	Water Level

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ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor, Dr. Mara Orescanin, for her guidance, instruction, and encouragement throughout the course of this research. Her dedication, wealth of knowledge, and enthusiasm for science has made the thesis process not only bearable but also educational. Thank you for being a great advisor as well as friend. I wish you the best of luck as you start your journey in the realm of government service. I would also like to offer my sincere gratitude to my second reader, Dr. Jamie MacMahan, for his support, expertise, and candor during the thesis process and the mountain biking.

I would also like to thank my cohort of former LDOs and Naval Academy graduates. I know we all feel the same way—that we could not have done this without each other's help. I can say that you are all not just classmates but friends, and I hope to hear of your successes as we continue our naval careers.

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I. MOTIVATION

The political state of the world is constantly changing. From the onset of the attacks of 9/11 until the drawdown of U.S. forces in Iraq and Afghanistan, the United States was in a land war in the desert. However, with that drawdown came the realization that the U.S. Navy, especially Naval Special Warfare and Expeditionary Warfare forces must return to the sea. Both of these forces operate in the littorals where the physical environment is highly variable and dynamic. One of the most dangerous operations in the armed forces is moving personnel and equipment from sea to shore. The land-ocean interface is the most challenging and variable affecting both vehicles and swimmers. If there is another factor, such as a river, involved, then the problem becomes ever more complicated. Having served with both of these Navy units, it is evident that a better understanding of the littorals is needed.

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II. INTRODUCTION

A. BACKGROUND

An ephemeral river is a river that flows only for a short period when there is heavy rainfall or snowmelt such that sufficient discharge exists in the river. For the rest of the year, the river channel remains dry; however, there is a good amount of groundwater beneath the riverbed and some pools may remain year-round. These smaller flowing rivers usually have a lagoon at the mouth due to wave action depositing sediment and closing the river mouth. Long periods of closures can aid in poor water quality, lagoon water rise, possible flooding of surrounding areas, and collection of debris that includes garbage and toxins (Davidson et al. 2008).

When the discharge is sufficient, the river flow can breach to the ocean, which has both positive and negative effects. The lowering of the water levels reduces any threat of flooding and opens a channel for fish to return to the ocean. However, this plume of lagoon water could contain pollutants and debris, which is mixed with the ocean. It could cause beaches to close for recreational purposes or hamper a naval operation by changing acoustic variability and rendering a beach landing unusable (Davidson et al. 2008).

Ephemeral rivers can be found around the globe in Northern Europe, the Middle East, Africa, India, New Zealand, Australia, parts of Latin America and the United States (Davidson et al. 2008; Ranasinghe and Pattiaratchi 2011). However, they are most prevalent in areas that are dominated by a Mediterranean climate, such as the coast of California (Behrens et al. 2013). Since there are periods of low water flow, the connection to the ocean is usually closed, forming a beach, and is classified as irregularly open. A narrow landmass, such as a barrier spit or barrier island, blocks the water from flowing into the ocean. The morphology of this narrow barrier is dependent on the state of flow of the river as well as the ocean forcing from waves and tides; however, the precise balance between land and ocean is difficult to determine.

A breach is a new opening in a barrier spit or barrier island that allows a river to flow into the ocean. A breach can occur naturally through several environmental processes (Hart 2007; Kraus et al. 2002) or artificially, with the help of man. Natural processes that lead to breaching happen either from the lagoon side (river discharge) or from the ocean side (wave overtopping and tides or storm surge), and predicting the location, timing, and duration of these breach events is challenging. Rain events cause water levels in the watershed to rise, as do waves from large storms breaking onto the beach and over washing into coastal lagoons, causing a gradual increase in water levels. This sometimes can be enough to allow a breach to occur by seepage and liquefaction but usually is short in duration, as there is not an eroded inlet and the wave forcing closes the breach (Kraus et al. 2002; Rich and Keller 2013).

Processes that contribute to breaching from the ocean into the lagoon include wave overtopping and tides (and the combination of both). Wave run-up on a smooth slope is a function of offshore wave height and beach slope (Komar 1998). Several studies have modeled the processes of wave run-up and overtopping, but there is a scarcity with regard to a river breaching a barrier beach (Kraus et al. 2002). Work by coastal engineers using the exceedance of the highest 2% of the wave run-up was conducted to measure the values for sloped dikes and seawalls with fewer studies being done on natural beaches. Through laboratory experiments, overtopping models have been developed but are designed to limit overtopping of levees and dikes, which is the opposite of this subject. More sophisticated models exist that take into account sediment transport (Basco and Shin 1999). A previous study compared three cases of wave overtopping and three different models to estimate the volume change of the water in the Carmel lagoon, which could be used to predict a breach (Laudier et al. 2011). All three models that were evaluated performed well in predicting overtopping but only after an ad hoc fix was applied to account for different wave direction and various beach morphology (permeability, roughness, and slope). Applying this model to other beaches will work only if they are similar in size and shape.

The purpose of this study is to analyze the processes that contribute to the water levels in the lagoon of the Carmel River and determine which one or which combination

of them will help predict if and when the river will breach. More recently, a breaching and closing model was developed using the Carmel River site that showed breaching and closure can be predicted but only when calibrated by minimizing the root mean square error between the observed and modeled 48-hour stage amplitude (Rich and Keller 2013). The model also assumes a straight channel flow directly from the lagoon to the beach as well as a fixed beach width and a channel inlet elevation not exceeding the elevation of the beach berm. All of which are necessary due to the dynamic nature of the lagoon/ocean interface.

The hypothesis regarding what processes contribute to changes in lagoon water levels is that discharge plays a dominant role when the river remains open due to the offshore pressure gradient (lagoon water levels are higher than the ocean), but that there are episodic openings and closures that are determined by wave and tidal forcing that balance this offshore pressure gradient. This hypothesis is tested by analyzing physical data (water level, temperature, salinity) that was collected from November 2016 to January 2017. Specifically, offshore wave heights and tides are determined and compared with discharge rates in the Carmel River to identify a balance of forces at the river mouth.

This paper is arranged into seven sections. Chapter III describes the experiment set up and the data that was used both field measurements and from other sources. Chapter IV looks at the methods used to evaluate the data, while Chapter V presents an analysis of the observations and findings. Chapter VI is the discussion, and is conclusion in Chapter VII.

B. ECOLOGICAL, ECONOMIC, AND NAVAL IMPACTS TO BREACHES

The societal relevance of ephemeral rivers is diverse, ranging from the ecological impacts of fish larval transport and salt marsh health to the economic impacts of flood risk to infrastructure to the naval impacts of littoral operations, namely beach landings. The reasons for a river to be artificially breached, in which a small channel is dug that will widen and deepen as the river scours the channel, are numerous. In the case of the Carmel River, which was used in this study, both ecological and economic impacts must be considered.

The estuary that is formed by the Carmel River is lined with multi-million dollar houses, including ones belonging to such famous actors as Betty White and Clint Eastwood, who also happens to be a former mayor of Carmel-by-the-Sea. During the winter months, when rainfall is more prevalent, the water levels in the lagoon may rise high enough to threaten the surrounding streets with flooding (Counts 2016), and therefore, the water levels are monitored regularly. In addition, next to the estuary and the main river channel is a wastewater treatment plant facilitated by the Carmel Area Wastewater District. If the water levels rise in the estuary, then it could potentially cause problems for the plant.

Ecologically, the lagoon and watershed are an important habitat for the federally threatened steelhead that are native to the Carmel River. During the parts of the year when the Carmel River and its tributaries go dry, many fish are stranded in small pools. Volunteers will move the fish to the calm waters of the lagoon, where they can grow and mature. However, the fish need the river to breach in order to reach the ocean and grow into adults, and the adults need to enter the river to spawn and complete the cycle. On the other hand, if the river breaches too soon and the current is too strong, those juvenile fish could be swept out to sea before they are mature enough and eventually die (Thomas 1996).

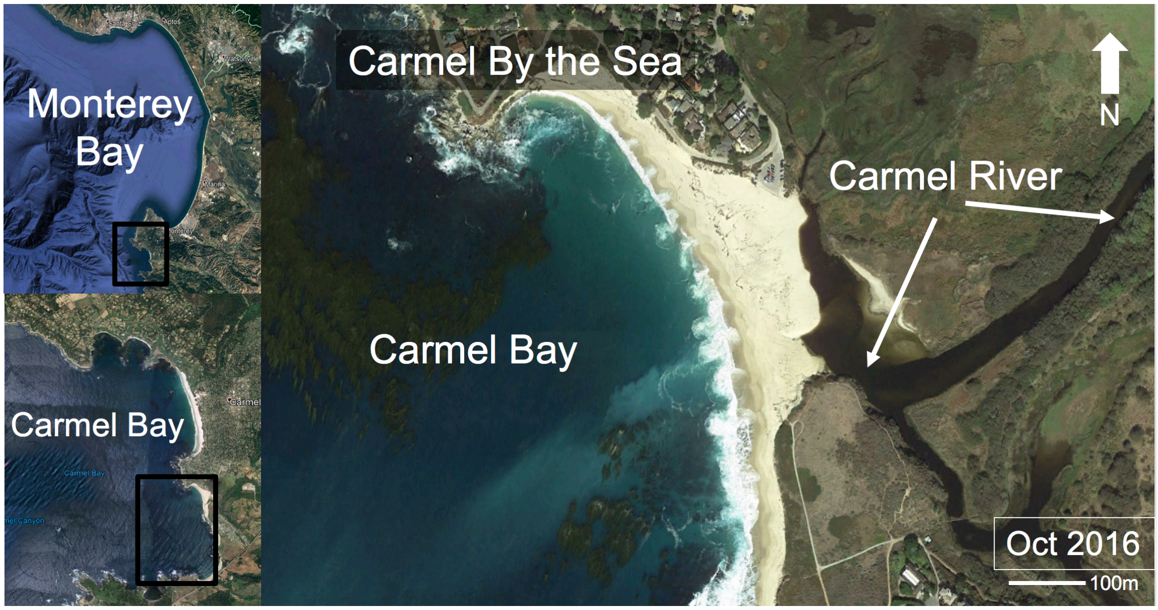
These two factors are important, but the focus of this study is changes in the beach morphology as it applies to naval operations. Intense and purposeful planning is always part of any naval operation, and a beach landing is even more difficult. The different environmental factors, such as currents, waves, tides, are hard enough to predict, and if the beach is changing as well, the operation becomes even harder to execute. When a river breaches, there are significant changes to the beach, which could cause damage to equipment, loss of human life, and the operation to fail.

C. CARMEL RIVER STUDY SITE

The Carmel River is located south of Monterey Bay on the southern end of Carmel Bay. It is bordered to the north by the southern end of Carmel-by-the-Sea and to the south by Carmel Meadows (Figure 1). The northern and southern edges of the beach

are marked with natural rocky outcroppings. The southern rocks prevent the Carmel River from migrating farther south during a breach. The Carmel River was first made famous by John Steinbeck, who wrote about it in his book *Cannery Row*. It was also listed as one of America's top ten endangered rivers in 1998, due to its misuse (March 2012). Nevertheless, it has made a remarkable comeback, especially since the removal of the San Clemente dam in 2015. It is a popular recreational area that attracts beachgoers, kayakers, birdwatchers and sometimes fishermen.

The Carmel River is only 58 kilometers long, but it drains a watershed of approximately 660 km^2. When there is a significant amount of precipitation, which occurs during the fall and winter, the lagoon water levels begin to rise. That factor in conjunction with the large waves that usually accompany those storms produce wave overtopping, which also increase the lagoon water levels. Previous models were developed trying to predict wave overtopping (Basco and Shin 1999; Laudier et al. 2011), but not all large wave events led to overtopping. On November 22, 2001, a large swell of 7–8 m was measured at the Monterey Bay Buoy, but at the same time, lagoon water levels remained at 6 feet through the duration of the event, indicating that no significant overtopping occurred.



Images retrieved from Google Earth with modifications added by the author.

Figure 1. Location of Carmel Bay and the Carmel River. Carmel Bay is south of Monterey Bay and the Carmel River mouth is on the southern end of Carmel Bay.

D. LAGOON INLET VARIABILITY

The highest variability and morphological changes that occur at the shoreline are associated with rivers that have highly variable flow (Barnard and Warrick 2010). This contributes to the difficulty in predicting timing, duration, and location of breaches. The Carmel River is a good example of this, as can be seen in Figure 2. When the river channel meanders from one location to another, the beach also changes, as does the concentration of sediment. It would be simple enough to measure the amount at the river mouth but with a dynamic system that is continuously changing, sometimes over a few hours, it is difficult to measure, owing to erosion and deposition rates. If a sensor was placed in one location, it might move or become covered with sand. It is because of this change and variability that placing a sensor in a breach would not be feasible.

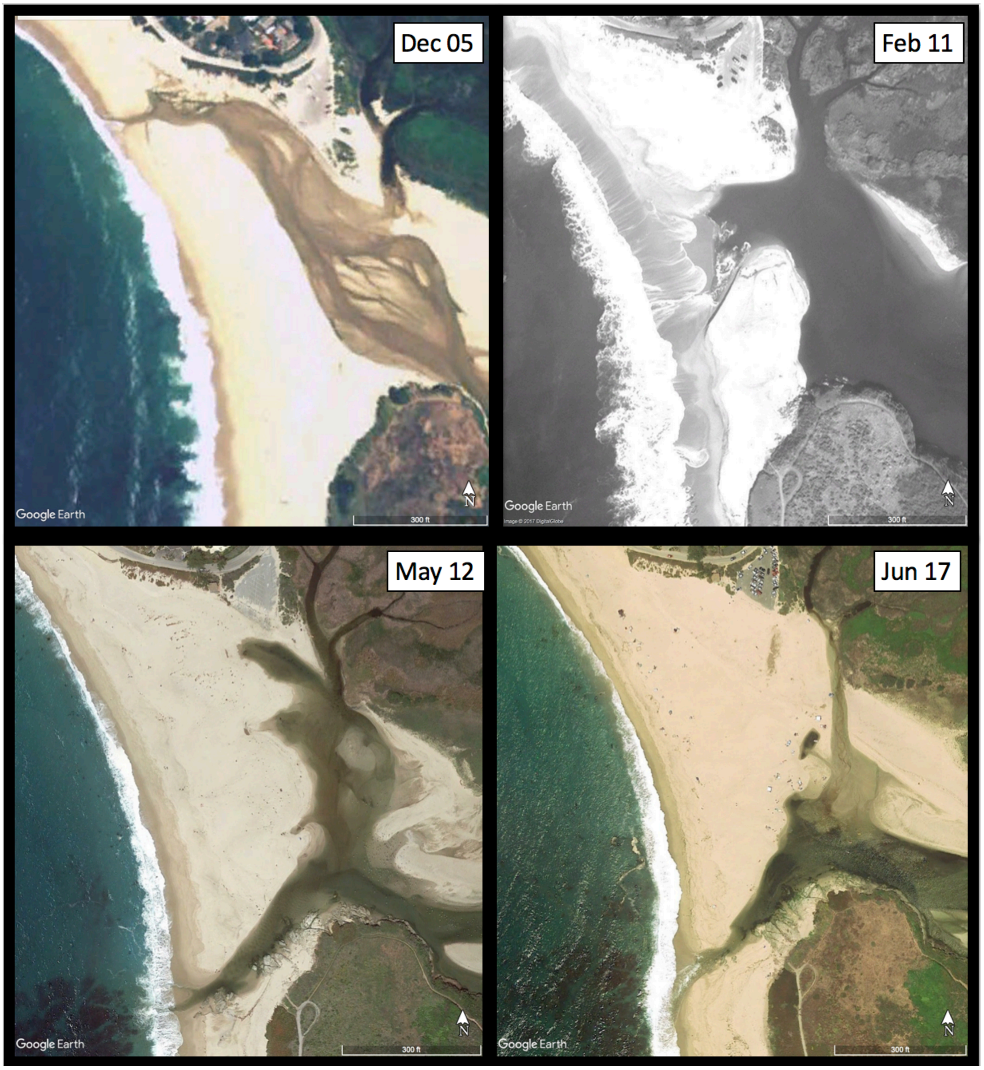


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Figure 2. Images showing variable morphology of the Carmel River mouth and inlet locations.

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III. EXPERIMENT SETUP AND DATA COLLECTION

A. INSTRUMENTATION

The data collected for this study were obtained from various sources spanning the winter months from 2016 to 2017. Observations were collected via in situ measurements from sensors that were placed offshore and in the lagoon (Figure 3). Two RBR Solo pressure sensors were placed offshore in approximately 15m of water and sampling at 2 Hz. The pressure data collected were used to determine water depth and in turn calculate offshore wave heights. These sensors were marked with a buoy and anchored with 70lbs of weight. Of note, an increase in the average raw pressure was observed in the data from the southern sensor indicating that it moved a short distance into deeper water while deployed but this did not affect the data collected. The offshore pressure sensors were in the water for 17 days, being deployed on November 14 and recovered on November 30.

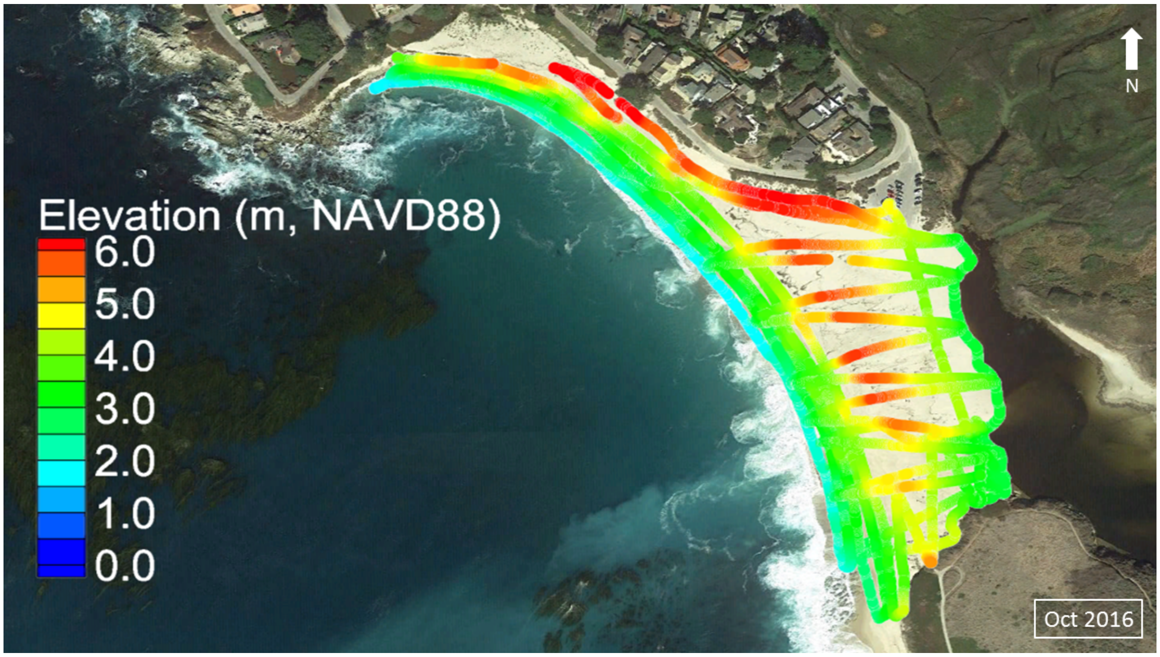
In addition to offshore sensors, one RBR pressure sensor was placed on the northern side of the river near the main channel where it widens into the lagoon at a depth of about 1 meter, and approximately 250m from the beach, also sampling at 2 Hz in order to measure any wave propagation upstream. In this same location, a conductivity, temperature and salinity (CTD) instrument, sampling at a rate of 1 Hz was placed to record temperature and salinity of overtopping events. Three Lowell Instruments TCM2 tilt current meters (TCM) were placed in the lagoon to measure velocity changes again from overtopping events, one near the CTD/RBR location, one in the southern arm of the lagoon near the Monterey Peninsula Water Management Districts (MPWMD) water level gauge at a depth of 5 meters, and one at the northern arm of the lagoon at a depth of 1 meter. These sensors were deployed on November 8 and recovered on December 9, 2016. The pressure sensor was replaced in the lagoon after the initial recovery and remained in the water until January 14, 2017. All of the sensors were anchored with a 35 lb. weight and secured to surrounding riverbank with a ground line.

Images retrieved from Google Earth with modifications added by the author.

Figure 3. Google Earth image showing the location of the 3 pressure sensors, 3 TCMs, the CTD, and MPWMD pressure sensor at the Carmel River study site.

B. BEACH MORPHOLOGY

A walking beach survey was conducted on December 08 2016 using an Ashtech ProMark 500 GPS system, which has a horizontal accuracy of 1cm and a vertical accuracy of 0.3 cm in order to measure berm height (Figure 4). Elevations are measured in NAVD88 vertical datum and corrected to compensate for antennae height. The average berm elevation was 5.5 m, with a depression in the berm near the southern end of the beach that measured 4.3 m.



GPS survey showing berm height. Red colors running down the middle of the beach from north to south is the peak of the berm, which averaged 6 m. Near the southern end (bottom of map) there is a depression measuring 4.3 m, which is the location of the initial breach.

Figure 4. GPS survey overlaid onto Google Earth image from Oct 2016.

C. OTHER DATA SOURCES

1. Significant Wave Height

Offshore wave data, obtained from the National Data Buoy Center, were collected from two buoys, one to the north of Carmel, station 46114, West Monterey buoy (WMB, #185) and one to the south, station 46239, Point Sur buoy (Pt. Sur, #157) to determine if there were any difference in wave height and direction that may affect the beach. Both buoys are Datawell Mark 3 directional buoys, and significant wave height (meters) is calculated as the average of the highest one-third of all of the wave heights during the 20-minute sampling period. All the buoy data are quality controlled by NOAA. Both were very similar in wave heights, 0.2m average difference, and direction (Figure 5), so only the Point Sur data were used, as the buoy was the closest to the field study site.

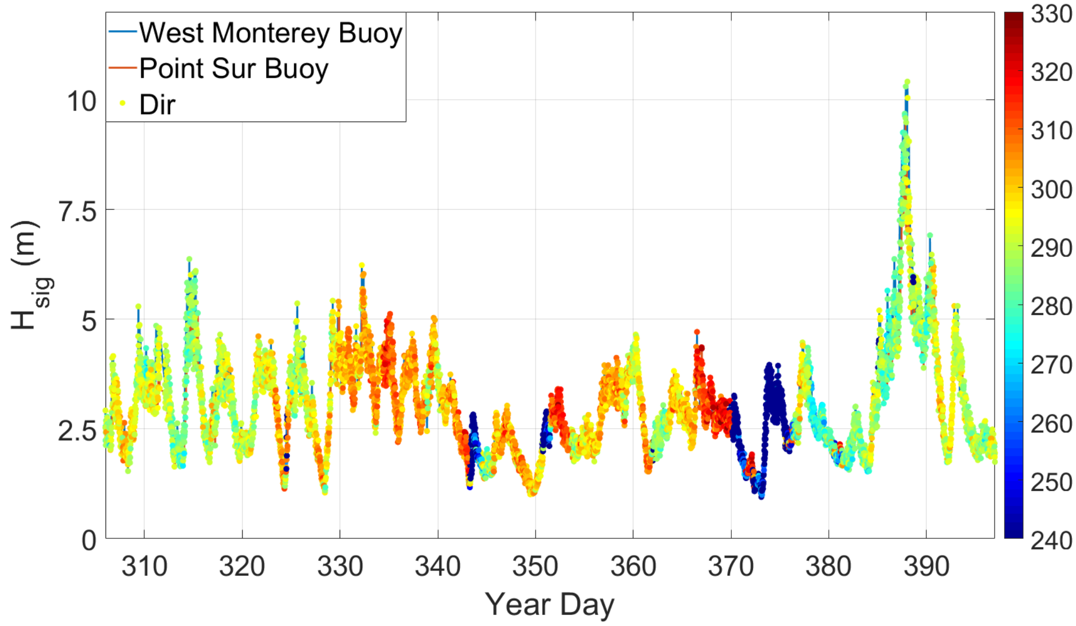


Figure 5. West Monterey and Point Sur buoys showing significant wave height colored coded by direction from Nov 1, 2016, through Jan 31, 2017.

2. Tides

The tidal data was obtained for the NOAA tides and currents webpage for Monterey, CA, station ID: 9413450, located at Monterey Bay municipal wharf. The accuracy of the NOAA tides is +/- 0.02m and referenced to NAVD88 datum. The estimated tidal lag between Monterey and Carmel River State Beach is less than five minutes, which is considered negligible.

3. Lagoon Water Levels

The lagoon water levels were obtained from MPWMD, which operates a pressure gauge in the south arm of the lagoon. Data are recorded every 15 minutes. Lagoon water levels are accurate to within 0.015m in comparison to a staff gage (James, 2009). The water levels are measured in NGVD29 but are converted to NAVD88 in meters with a conversion of +0.833m, which is based on the latitude and longitude according to the National Geodetic Survey (NGS) orthometric height conversion tool (NGS, 2009).

4. Discharge

River discharge was collected again from MPWMD, which maintains several stream flow gaging stations along the river's path. The data used for this study are from the sensor located at the Highway 1 bridge, which is approximately 1 km to the east.

All the above data were plotted versus yearday to visually interpret water levels against tides and discharge (Figure 6). Calculated lagoon water levels from the RBR pressure sensor at location 2 was plotted against MPWMD measured water levels as a guide to ensure calculation accuracy.

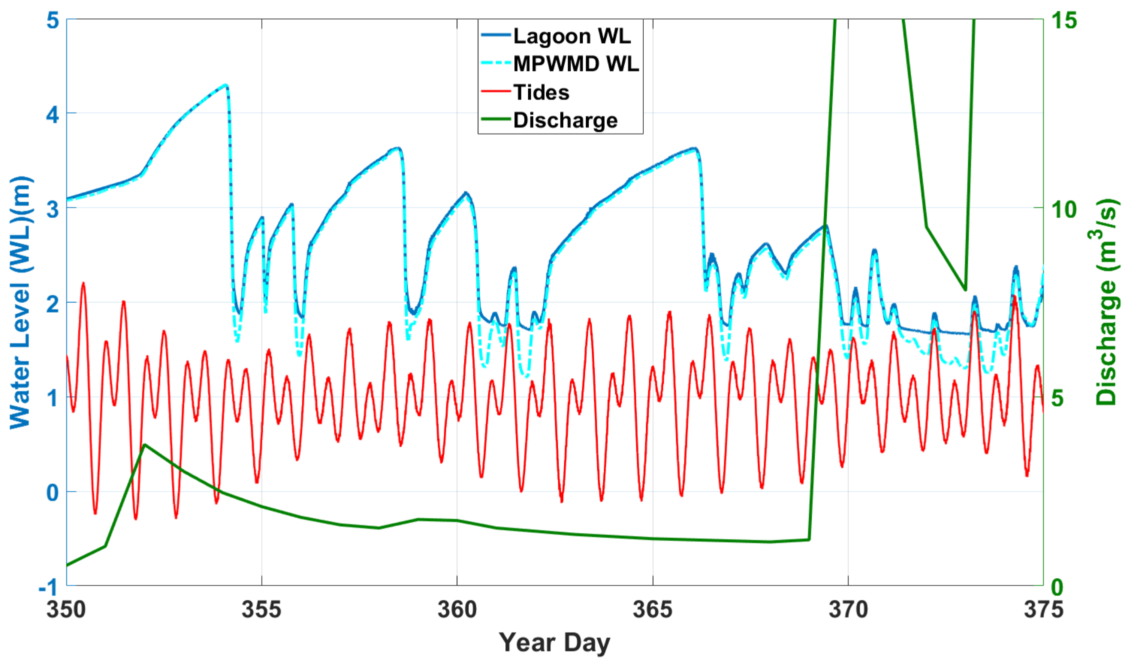


Figure 6. Calculated WL (dark blue) and MPWMD WL (cyan) in meters are plotted with Monterey Bay tides and river discharge in cubic meters per second from yearday 350 (Dec 19, 2016) to 375 (Jan 9, 2017).

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IV. METHODOLOGY

The observations spanning November 2016 through early January 2017 demarcate two distinct river states prior to the full opening on January 4, 2017. Specifically, until the initial breach on December 19, the river remained closed and was dominated by wave overtopping. After the initial breach, the river cycled through seven distinct breaches. The breaching and closure events were determined by looking at the lagoon water levels that were calculated from the pressure sensor in the lagoon in conjunction with the MPWMD water levels.

A. WATER LEVELS

Pressure sensor data collected was converted to water levels by using the sea water depth function in MATLAB (Figure 7). Atmospheric pressure was taken into consideration and was subtracted from the raw pressure. A correction factor was applied to convert the data to NAVD88. For the back-lagoon sensor, the peak water levels were adjusted to the Monterey Peninsula Water Management District's water level gauge in order to convert the data to NAVD88.

1. Breaches

A breached was called when there was a rapid drop in lagoon water levels. If the drop was greater than the tidal range and the time it took was greater than a tidal cycle (about 6 hours) or if the drop was less than the tidal range and shorter than a tidal cycle.

2. Closures

A closure was called when lagoon water levels begin to rise and continued to rise as the tide cycle was falling.

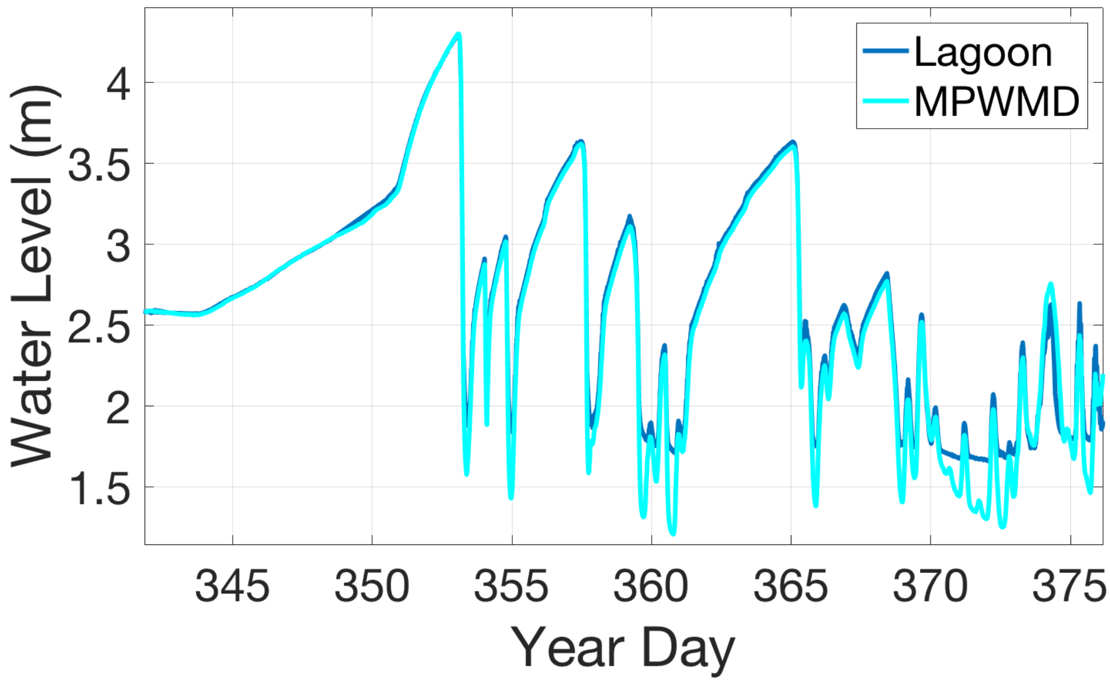

Figure 7. Calculated lagoon WL (NAVD88) in blue with MPWMD water level in cyan from before the first initial breach through full opening.

B. WAVES

1. Calculated Wave Heights

Wave heights were calculated from the offshore pressure sensors by using linear wave theory (Dean and Dalrymple 1991) where pressure was converted from the time-domain into the frequency-domain using spectral decomposition which yields pressure under a wave:

$$P = -\rho g z + \rho g \frac{H}{2}\frac{\cosh(k(h+z))}{\cosh(kh)}\sin(kx - \omega t)$$

The pressure time series were first high-pass filtered to remove any effects from low frequency phenomena (tides, changes in discharge, etc.). The pressure power spectral density was then calculated in order to reduce the confidence intervals (spectral smoothing). By converting the pressure power spectral density to water elevation power spectral density, the depth decay under a wave is accounted for and estimates of the significant wave height are possible (Thornton and Guza 1983)(Figure 8). This similar

method was also used for measurements obtained within the lagoon during closure events to indicate times where significant wave energy penetrates the lagoon. (See Chapter V for more description.)

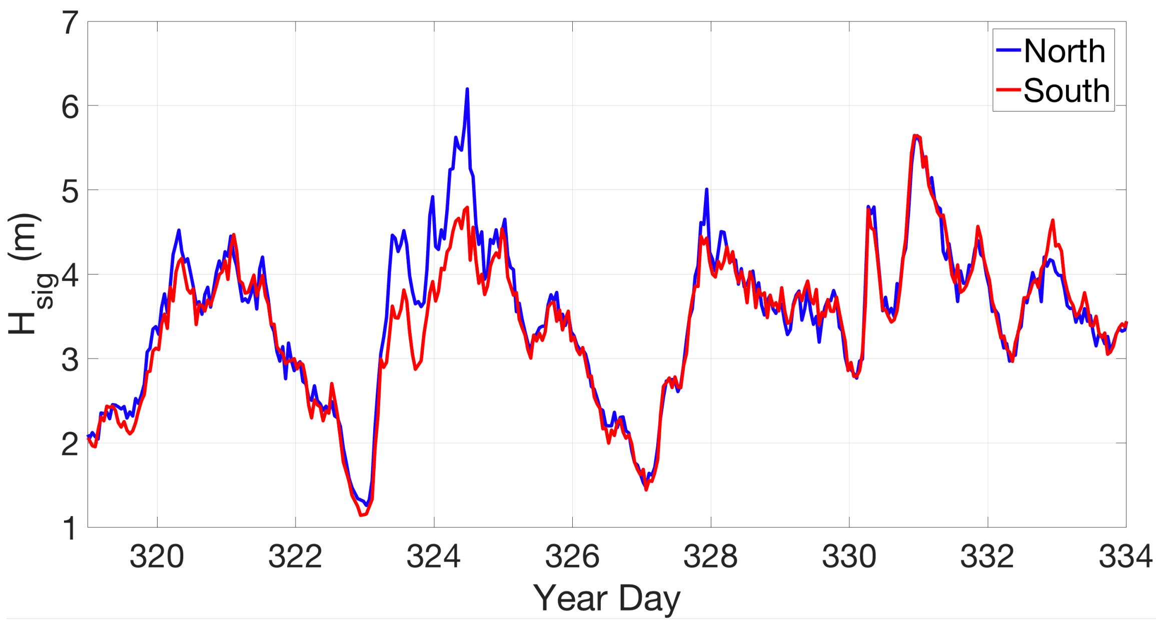

Figure 8. Calculated Significant wave heights from offshore pressure sensors.

2. Point Sur Buoy Wave Heights

Much of the breaching and closure cycle occurred after the offshore pressure sensors were retrieved from the water. The calculated wave heights from the offshore sensors were compared to wave heights from the Monterey buoy and the Point Sur buoy to determine accuracy by taking the difference between the calculated wave heights and the buoy wave heights over several days and averaging the delta and determined to be accurate within 0.5m. Therefore, the Point Sur wave heights are assumed to represent the offshore forcing at Carmel River during times when measurements were missing.

C. MOMENTUM BALANCE

It is hypothesized that a balance between river discharge (dynamic pressure) and ocean forcing from tides and waves will balance and cancel at the breach during closure events. To test this hypothesis, estimates of each forcing mechanism are included in a momentum balance for the breach. When the velocity of the flow at the breach is strong enough, then the channel will remain open. When the velocity decreases and is close to zero, sediment is accreted in the mouth of the breach. In order to determine the discharge through the channel, Q_{Out}, a momentum balance was estimated (Malhadas et al. 2009; Orescanin et al. 2014; Wargula et al. 2014)(Figure 9) that uses the upstream discharge from the river, Q_{River}, as the upstream condition to the lagoon, and that uses both the cross-shore gradient in wave radiation stress, S_{xx}, and the pressure gradient between the lagoon and the ocean, η_L-η_o.

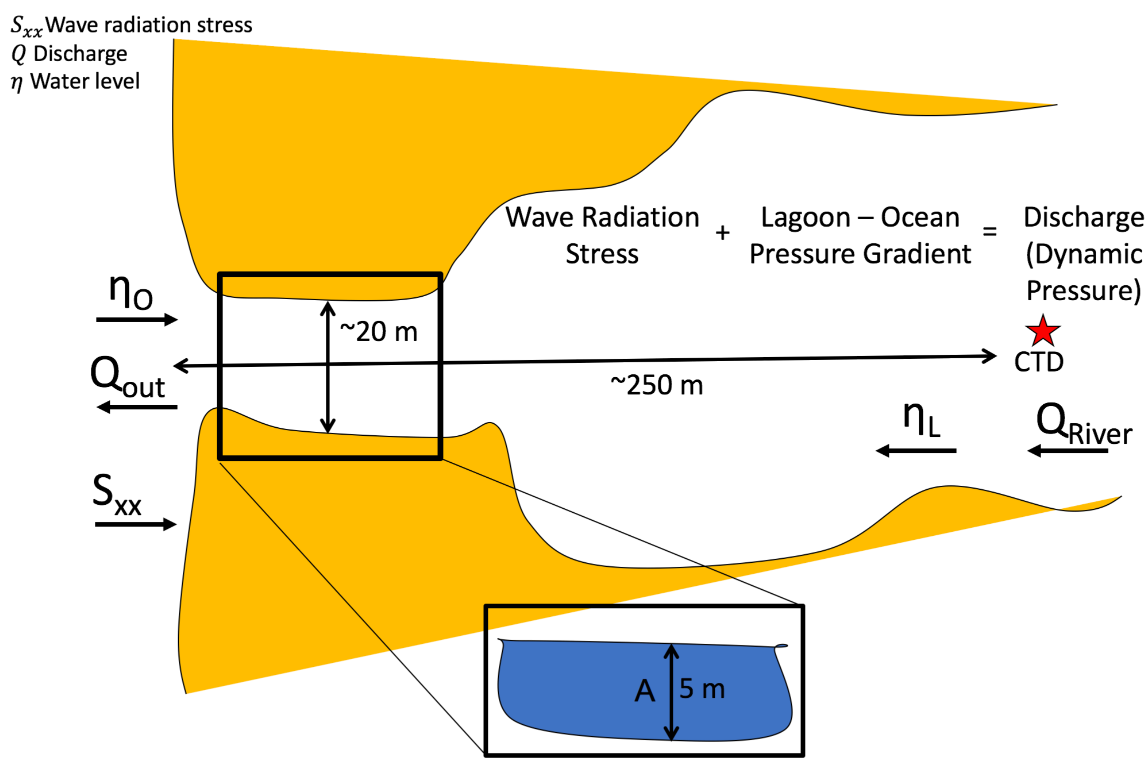

Figure 9. Momentum balance Q_{out} was estimated by using the known measurements of Q_{in} is river discharge, η_L is lagoon water level, η_O is ocean water level, and the calculated wave radiation stress S_{xx}.

It is expected that when the discharge at the breach, Q_{Out}, is zero or close to zero, sediment can be deposited leading to a closure. However, it is difficult to measure Q_{Out} over long time periods owing to the complex morphological variability of the channel itself as described previously. In order to determine the momentum balance between ocean and river forcing, the following equation is used to infer what Q_{Out} is by using known measurements such as the river discharge, lagoon water levels, and ocean water levels:

$$Q_{River} + Q_{Ocean} = Q_{Out}$$

where Q_{River} is the water levels from the MPWMD water gauge and Q_{Ocean} is the offshore forcing. From this equation, the hypothesis that when Q_{Out} is small correlates with closure events can be tested. The forcing contribution from the ocean can be furthermore broken into contributions from waves and from tides as:

$$Q_{Ocean} = Q_{Tides} + Q_{Waves}$$

Q_{Tides} can be expressed by

$$Q_{Tides} = \Delta t \left(g \frac{\Delta \eta}{\Delta x} \right) A_c$$

where Δt is the time step between measurements of η, g is the acceleration due to gravity, $\Delta\eta$ is the difference between η_O, the tides at Cabrillo Point and η_L, the measured lagoon water levels. The distance between the beach and the sensor is Δx and $A_C = b * h_c$ is the area of the channel. The width, b, was estimated by using photos taken during a breach as well as satellite imagery and multiplied by h_c, the water depth in the channel, which was estimated, plus the tide. The are no direct measurements for these and they change over time but this equation is a good estimate of the water flowing through the channel.

The wave forcing, Q_{Waves}, resulting from breaking waves imparting momentum to the water column near the breach, can be expressed by

$$Q_{Waves} = \Delta t \frac{\partial S_{XX}}{\partial x} b$$

where Δt is the change in time, $\frac{\partial S_{XX}}{\partial x}$ is approximated as $\frac{3}{16}\frac{gH_B^2}{\Delta x}$ and Δx is the width of the surf zone that is dependent on the slope of the beach, b, and is assumed to be 1/10, which is consistent with previous studies on the same beach (Laudier et al. 2011).

In this simplified model, there are several assumptions being made that should be addressed. First, it is assumed the tides at Cabrillo Point are the same at the beach. This assumption is reasonable because any change in the tides are considered negligible, owing to the five-minute lag between the tide gauge and Carmel River. Second, it is assumed that the breach occurs in a straight line across the beach, from the lagoon to the beach. This is reasonable because all observations of initial breaches were directly across the beach, and the measured water levels indicate values that would approach the berm height indicating spilling. Third, only external forcing is considered (no groundwater or runoff) from the river and from the ocean, such that the only method for increasing water levels within the lagoon come from the river discharge and the ocean (tides and/or waves). Fourth, friction is neglected within the lagoon. This may or may not be a reasonable assumption, especially near the breach itself, however, it is assumed that friction would act equally and opposite on both the river discharge as well as the ocean discharge such that the effects would cancel. Further work is required to validate this assumption.

We can test how sensitive the results are to errors in estimates of geometric parameters (breach width, breach depth, breach orientation, beach slope, etc.) by changing the values of the area and comparing the resulting changes to total discharge. The maximum depth of the bedrock is 18 m (Feeney and Gardner 1989), which would be the bottom boundary condition for breach depth. During these breaching and closure events, the banks of the channel were fairly steep such that the width is not expected to vary over a tidal cycle. For the initial breaches, the width is assumed not to change over

the breach, which is likely an over estimate of the width given the initial breaches closed almost immediately. Using typical conditions from point measurements from photos and from satellite imagery, the width used is 20 m. Sensitivity to these estimates are included in the discussion.

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V. RESULTS

In order to determine if and/or when the river will breach or close, several factors such as discharge, wave action, tidal stage and cycle, must be accounted for. If the discharge is significantly large then a breach will happen and remain open. However, if there is just enough discharge that is balanced by offshore forcing, i.e., waves and tides, then the jet strength will be decreased enough to allow sediment to be deposited into the breach and eventually close it up.

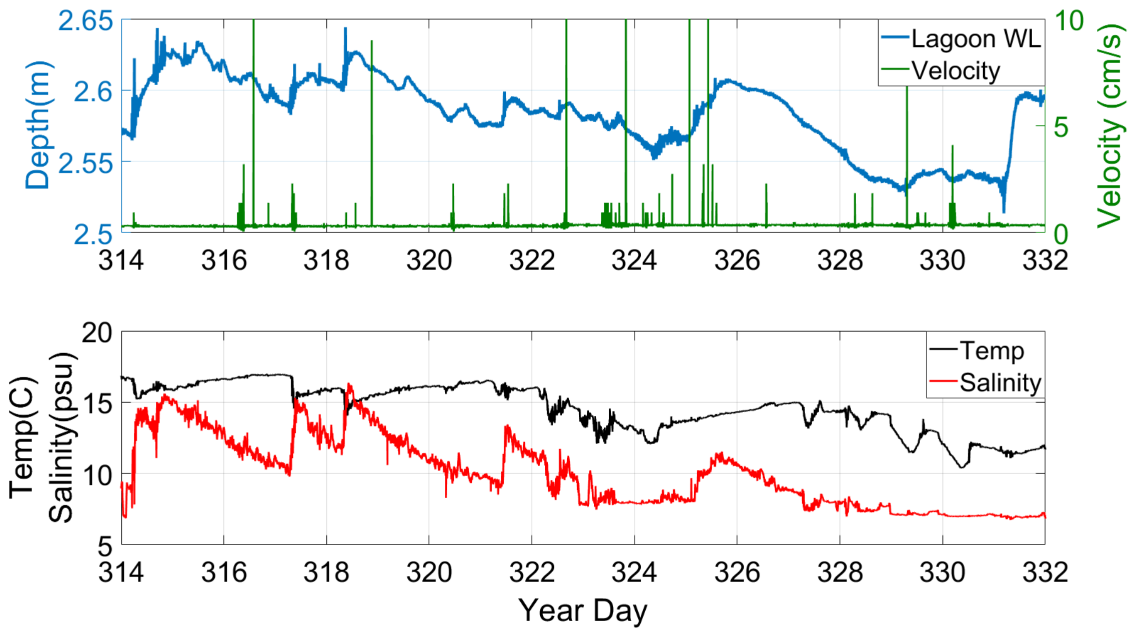
A. WAVES

1. Surface Gravity Waves and Breaching/Closure

It is hypothesized that offshore energy forcing (waves and tides) and onshore forcing (discharge/precipitation) are the two major factors that will determine if the river mouth will open or close. Large waves and high tides which typically happen during the winter months could be enough to balance weak river flow and are favorable conditions for periodic breaching and closure events. A closer look was taken at the lagoon water levels at location 2 and were overlaid with MPWMD readings to ensure accuracy. Due to the location of the MPWMD gaging station, which is located in the south arm of the lagoon, pressure sensor is in deeper water that is why there is a difference in water levels when a breach occurs, but the water levels are consistent after a closure and the lagoon water levels begin to rise. Wave height and direction were also examined from the two offshore buoys but no discernable difference was noted. Before day 350, the river was closed and the discharge was minimal or zero.

Large waves did occur prior to 350 as well with wave heights ranging from 2.5 m to 6.5 m producing some wave-overtopping. An increase in salinity and a corresponding decrease in temperature was seen in the CTD data as well as an increase in current velocity from the TCM at location 2 and an increase in variability in the water levels confirming this, however there only an increase of on the order of a few cm in the lagoon water levels during these events (Figure 10). There was also the appearance of small tidal fluctuations, which were not further considered. Together with the longer term (synoptic

scale) variations with water level suggest possible influence of permeability of the dune and evaporation within the lagoon.



Lagoon WL with TCM current velocities from location 2 (top). CTD water temperature and salinity (bottom).

Figure 10. Wave overtopping events prior to initial breach.

After day 370, the river was fully open due to a large storm and significant amount of precipitation increasing river discharge by two orders of magnitude. During a 25-day period (yearday 350 to 375), a series of seven distinct breaches and closure events occurred (Figure 11).

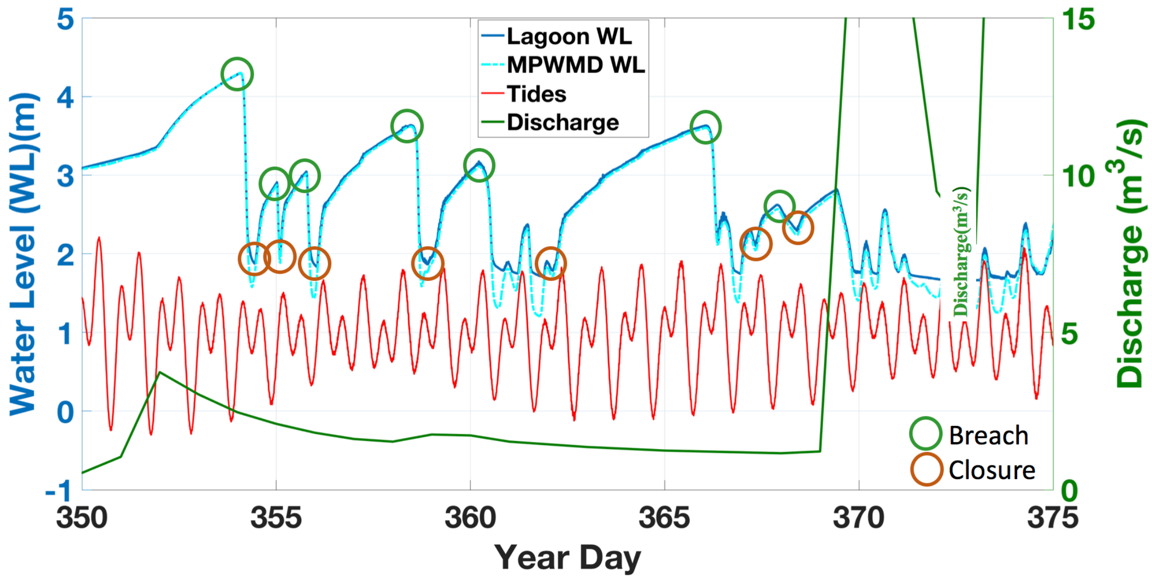


Figure 11. Time series of water levels in the lagoon and ocean during a 25-day period from yearday 350 (Dec 17) through year day 375 (Jan 9), showing seven distinct breaching and closure events. Green circles indicate breaches and brown circles indicate closures.

All seven of these breach-closure events were carefully examined to determine what the ocean forcing factors were during each breach and closure (Table 1). The calculated water levels from the pressure sensor at location two along with tides, significant wave height and direction. Multiple pictures were taken during this time frame, and some of the breaching and closure events were captured on film (Table 1). Discharge was nearly constant throughout this period except for the first spike on day 351 and therefore was not taken into consideration. A breach was determined when there was a sharp decrease in water level to when the water level bottoms out and begins to rise again. The duration of each breach varied among all seven events with the average lasting 6.5 hours, the longest 12 hours, and the shortest lasting only 2.4 hours (Table 2). The breach that lasted 12 hours breached in two stages that were both shorter than the half tidal cycle. A closure was called when the lagoon water levels began to rise again and when there was a separation of the lagoon water levels and a falling tide. The closures also varied in time with the shortest lasting 9.6 hours, the longest lasting 88.8 hours (3.7 days) and the average being just over 1 day (1.2).

Table 1. Seven breaching and closure events with corresponding measurements.

	OPEN							CLOSE					
Event	Day	WL	Tide	H_{Sig}	Dir	Photo		Day	WL	Tide	H_{Sig}	Dir	Photo
1	354.1 (Dec 19)	3.45	1.38 (high)	2.1m	285	Yes		354.5 (Dec 19)	1.06	0.95 (rising)	2.1m	305	Yes
2	355.0 (Dec 20)	2.04	0.93 (rising)	2.5m	295	Yes		355.1 (Dec 20)	1.19	1.31 (rising)	2.2m	300	Yes
3	355.8 (Dec 20)	2.18	.0.7 (falling)	2.1m	295	Yes		356.1 (Dec 21)	1.01	0.96 (rising)	2.0m	295	Yes
4	358.5 (Dec 23)	2.79	0.48 (low)	3.4m	305	No		358.9 (Dec 23)	1.04	1.00 (falling)	2.7m	295	No
5	360.2 (Dec 25)	2.3	1.69 (rising)	4.1m	290	No		361.2 (Dec 26)	0.925	1.42 (rising)	2.4m	300	No
6	361.5 (Dec 26)	1.53	0.88 (falling)	1.5m	310	No		361.9 (Dec 26)	0.878	1.01 (rising)	2.1m	295	Yes
7	366.1 (Dec 31)	2.79	1.173 (falling)	2.3m	300	Yes		367.0 (Jan 01)	0.947	1.17 (rising)	4.3m	320	No

Column 1 is the event (i.e. event 1 is first event and first closure), Day is the yearday the event took place, WL is the measured water level for the event, tide is the measured tide during the event, H_{Sig} is significant wave height from Point Sur Buoy during the event, Dir is the wave direction, and Photo indicates whether a picture of the river was taken during one of these events.

Table 2. Breach duration.

Event	Start	End	Duration
1	354.1	355.4	7.2
2	355	355.1	2.4
3	355.8	356	4.8
4	358.5	358.7	4.8
5	360.2	360.7	12
6	361.5	361.8	7.2
7	366.1	366.4	7.2

Start is when the breach started and end is when the water levels bottomed out before starting to rise again.

There was no correlation between when the river breached and high wave heights and or tides. Prior to the first breach, there were larger offshore wave heights in

conjunction with a small increase in discharge. The overtopping and the increase in precipitation could be enough to raise the water level for the first breach. As the wave height decreased in the following days, by 1.25 m, the discharge could have been enough to create a breach. However, over subsequent days, the wave heights remained constant and the discharge decreased. During that period two distinct breaching and closure events occurred. The next closure occurs when the wave heights again increase to 3.5 m and the river remains closed for over a day. A breached occurred just before a small decrease in wave heights, so again wave overtopping could be enough to cause a breach. Then wave heights increase and a closure occurs right after that. Once the wave heights start to decrease below 3 m there is another breach that lasts just over two days. This is determined by the water levels mimicking the tidal cycle. When the waves again start to increase on day 362 another closure occurs and remains so for 3.7 days. The next breach occurs on day 366 when there is a large increase in offshore wave heights, from 2.3m to 4.0 m. After this breach, the lagoon water levels again mimic the tidal cycle for almost a day indicating the river remained open. During this opening the wave heights decreased by only slightly. When there was a small increase in wave heights there was another closure but of short duration. There is a small correlation of a decrease in wave heights corresponding to an opening but it is hard to tell as the wave heights vary so much. However, when examining the closure events, all occurred either during a rising tide or at high tide.

2. Infragravity Waves

Infragravity waves with periods ranging from 0.4 - 4 minutes (Herbers et al. 1995) are found in all parts of the ocean but are most prevalent at the coast. Upon closer examination of the lagoon water levels when the channel began to close small oscillations could be seen (Figure 12) in the variance of the lagoon signal.

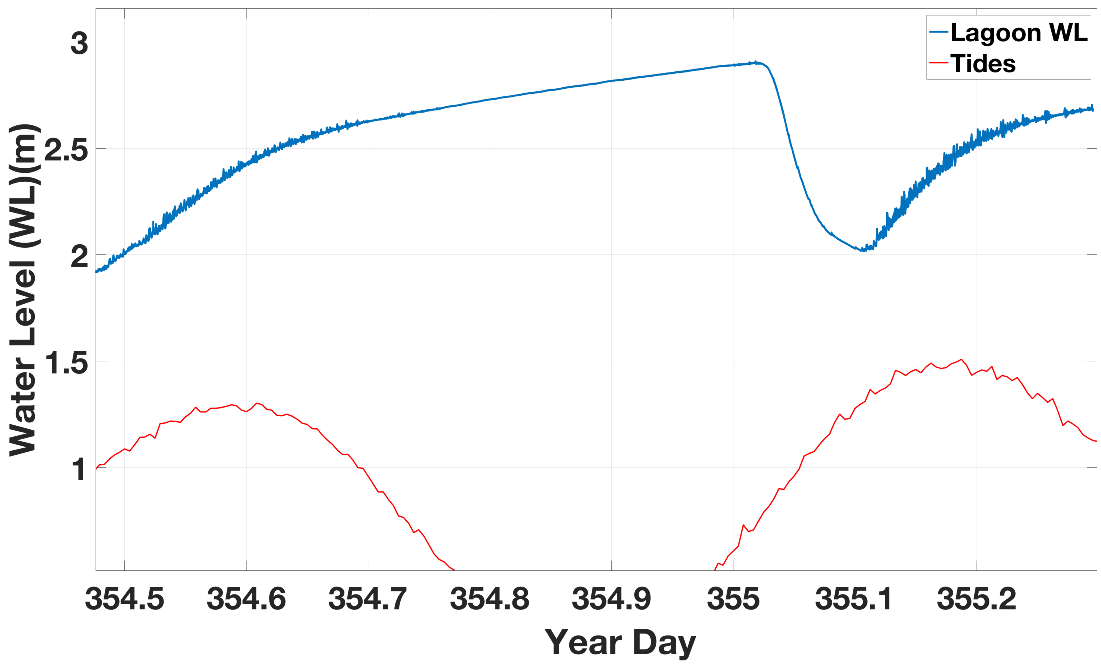


Figure 12. Enlarged plot of lagoon water levels showing the variability of the pressure signal.

The pressure sensor data was converted to a frequency spectrum, similar to the wave height calculations in section IV, and all of the energy fell within the low frequency swell and infragravity ranges (Figure 13). Since the infragravity energy was measured at the pressure sensor 250 m from the shore it indicates that there was a connection to the ocean but all the swell and wind waves have decayed and the only energy that is reaching the sensor is from the infragravity waves (Bertin and Olabarrieta 2016). When those oscillations completely stopped, the channel is considered to be completely closed. What is important here is that all of the swell wave energy has decayed which indicates that the swell energy has been blocked by the river discharge.

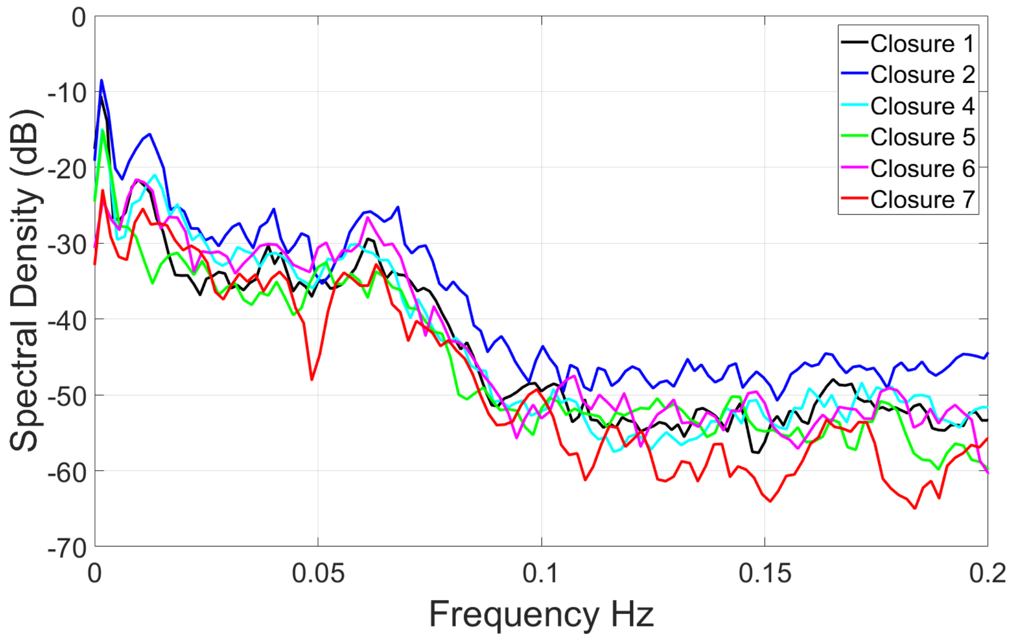
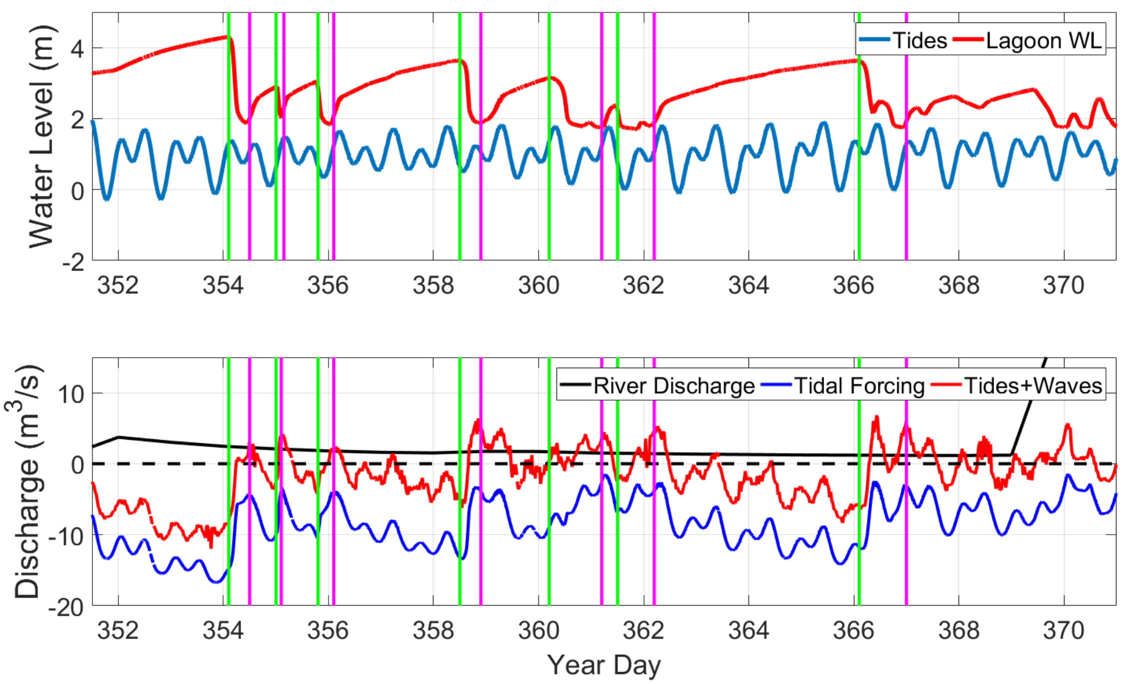


Figure 13. Spectral density plot of the seven closures showing the presence of infragravity waves.

B. MOMENTUM BALANCE

Since there is always an offshore pressure gradient between the tide and the lagoon water levels, water is inclined to flow from the lagoon to the ocean when there is a breach. However, since it is observed that the breach closes periodically, forcing from the ocean must play a role. The momentum balance using discharge was estimated during the breach/closure cycles and compared to the water levels of the lagoon and tides, both referenced to NAVD88 (Figure 14 top). An important observation is that since the tides are never higher than the lagoon water levels there is always an offshore directed pressure gradient. The water levels were compared to tidal forcing and tide plus wave forcing against the river discharge (Figure 14 bottom). Here, positive discharge is offshore for the river and onshore for the ocean (i.e., both tides and river present offshore forcing). Breaches are indicated by green vertical lines and closures are indicated by magenta vertical lines. With just tidal forcing alone, there is insufficient ocean forcing to counter the river discharge. In fact, under this estimate, there is always an offshore-directed discharge. However, when the tidal forcing is combined with wave forcing, there are times where the ocean forcing (tides plus waves) is positive and therefore onshore. The

periods of closure (magenta lines) occur when there is strong onshore forcing. The first breach occurred on day 354, two days after an increase in discharge. At this time, there was not favorable onshore ocean forcing, which is consistent with the generation of an offshore-directed jet. This is a consistent observation at each of the breach events: breaching occurs when there is favorable offshore forcing and insufficient wave energy to force closure. In addition, closure occurs at the first instance post-breach of onshore directed forcing. It should be noted that not every offshore-favorable time creates a breach and that all breaches occur at varying water levels in the lagoon. This suggests that berm height is a likely variable contributing to the timing of breaching. The same pattern can be seen during each event.



The tides are always below the lagoon water levels indicating a head force offshore (top). Time series showing river discharge in black with tidal forcing in blue and tidal plus wave forcing in red (bottom). Green lines indicate breaches and magenta lines indicate closures. When the tidal and wave forcing is below the discharge, a breach occurred, when the tidal and wave forcing is at or above the discharge, a closure occurred.

Figure 14. Time series plot of lagoon water levels versus tides (top) and momentum balance with tides and tides plus ocean forcing (bottom).

VI. DISCUSSION

Breaching and closure events are typical for ephemeral rivers. Breaching can occur in one of two ways: first, if water flows over the top of a beach barrier, either from the lagoon or from the ocean, it scours a channel (or flows through an existing depression), causing failure of the beach. Second, if a beach barrier is relatively narrow and porous, then liquefaction occurs and water-sediment mixture is carried away by wave action (Kraus and Munger 2008). For a closure to occur, it is dependent on the scouring of the offshore current and the amount of sediment deposited near the channel due to wave action. If the offshore current, hereby referred to as the jet, cannot overcome the sedimentation then the inlet will close (Behrens et al. 2013).

A. BREACHES AND CLOSURES

The first type of breach is often the case along the California coast and commonly occur from the lagoon side in contrast to breaching from increased ocean forcing (such as storm surge). When there is an increase in water from either groundwater, river inflow, or precipitation, and the lagoon reaches a certain height, the beach barrier can no longer hold back the water and a breach will occur. This usually happens where the barrier is at its narrowest and lowest elevation. Prior to the first breach, the southern end of the beach was lower and narrower than at any other location as was measured by the GPS survey and seen in the many photos that were taken. Wave overtopping was observed on many occasions (Figure 15) in the depression of the beach berm that was seen from the GPS survey. The overtopping is quite possibly responsible for scouring the berm height even further and creating a lower depression. In the top plot of Figure 12, it is clear that the lagoon water levels are always higher than the ocean. When a slight increase in the discharge occurred, water levels rose to 4.5 m, which was enough for the water to spill over the berm and initiate the first breach. This is illustrated in Figure 16.

Figure 15. Picture taken November 17, 2016, of wave run-up and overtopping in to the lagoon scouring the berm height.

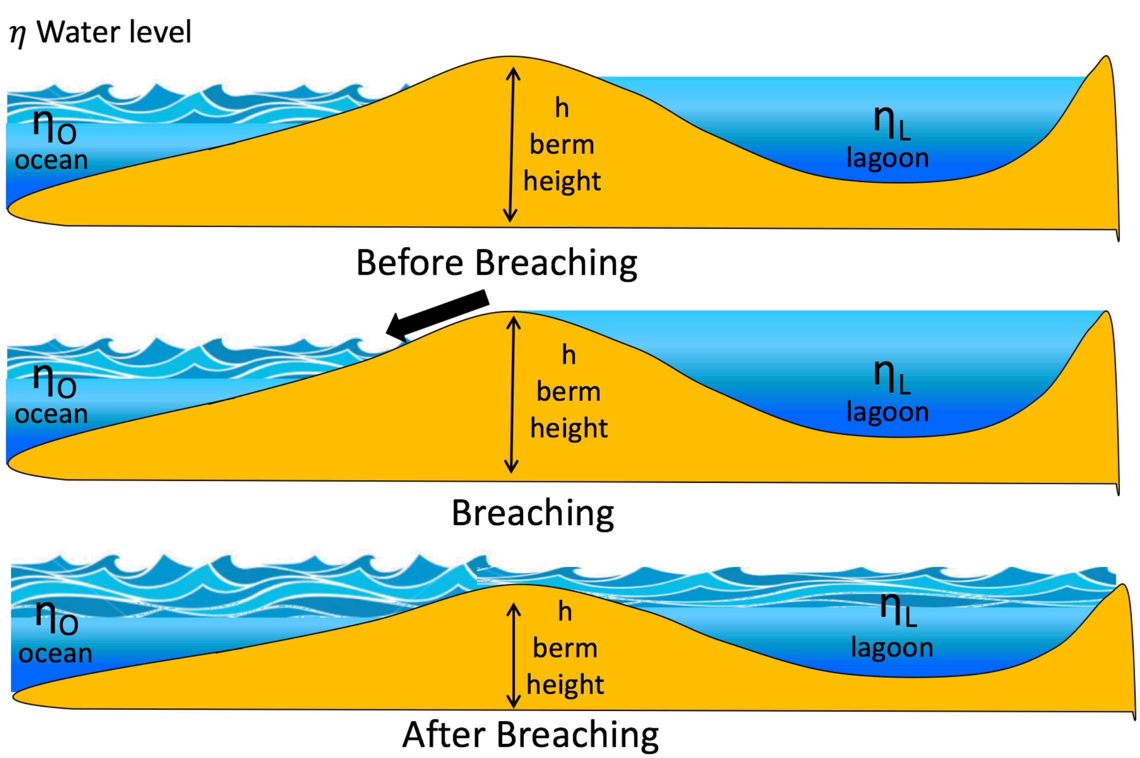


Figure 16. Graphical depiction of the Carmel River breaching from the lagoon side.

The breach remained open, but the duration was not significant enough to dig a deep channel and when the wave energy increased, the flow was counter balanced by the tide and waves enough to where sediment could be deposited to close the channel up. The water levels dropped after the first initial breach on day 354, and the jet was strong enough to keep the breach open for nine and a half hours. As the tide began to rise plus the addition of wave action, sedimentation occurred at the mouth of the channel. When the tide starts to fall, the newly deposited sand had built the berm up high enough to temporarily block the channel.

Typically during the winter the monthly precipitation (and consequently discharge) are higher and when the discharge exceeds 5.5 m^3/s the channel will not close (James 2005). On day 370 there was a big increase in the river discharge from 1.2 m^3/s to 22 m^3/s, which was significant enough to open the channel and keep it open through the next six months. The jet was able to penetrate the surf zone regardless of how high the wave heights were. If the offshore jet is strong enough then it will propagate though the surf zone and the wave energy will not penetrate the channel therefore not sediment can be deposited in the channel closing it up (Figure 17).

Figure 17. Picture taken Jan 22, 2017, during a breach when the discharge was 56 m^3/s. This was strong enough to prevent offshore waves from entering the channel

Even when the discharge decreased in the spring and early summer to the same discharge levels as the first initial breach-closure cycle, the river remained open because the wave energy significantly decreased as well and there was no more wave blocking. There was not enough wave forcing to counter the force of the jet, albeit weak, to close the channel up until the discharge fell below .5 m^3/s, which happened in mid-July (Figure 18).

Figure 18. Picture taken July 17, 2017, of the river after it finally closed.

One other variability that occurred during the study was the orientation of the channel. The first breach occurred near the southern end of the beach and remained there for a couple of weeks; however, by January 17, the channel had migrated to the north by approximately 400m. Over the next two months, it was observed to switch from the north to the south and back again three more times (Figure 19). There are times when there is a wave height gradient between the north and south side of the beach (Figure 8), which could create a longshore current and possibly explain the migration. However, further study needs to be done on this matter.

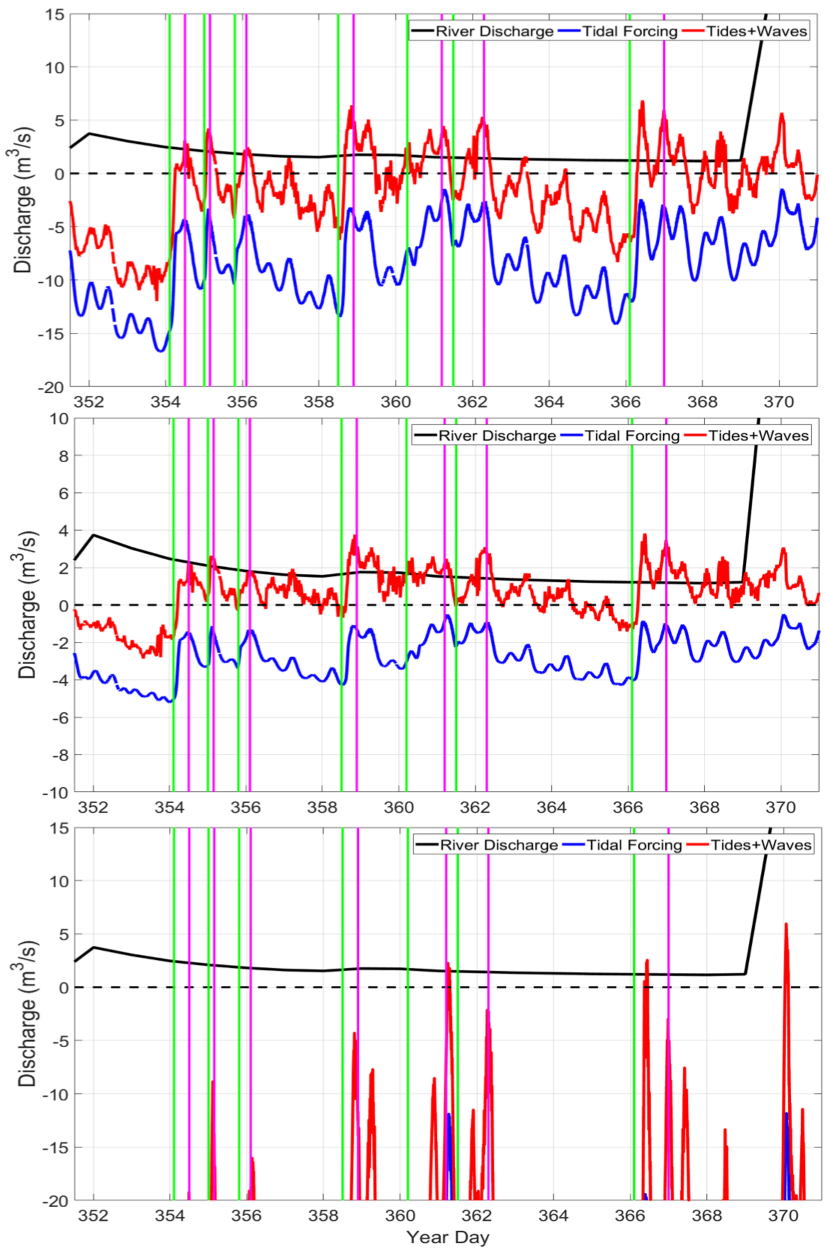
Figure 19. Photos showing the different locations of the channel after the river remained open.

B. MOMENTUM BALANCE

During the 18-day period when the episodic breach and closure events were observed, there was an equilibrium that occurred when the discharge rate balanced the ocean forcing, however only briefly. In order for a breach to remain open, the opposing force must be sufficiently weak, and for a breach to close the opposing force must be sufficiently strong. The hypothesis tested here is that wave forcing is always necessary in counter acting the offshore pressure gradient and acting against the jet leading to a closure.

The momentum balance estimated here used average depth and average width of the breach channel, which does change over time as can be seen in photo taken during a breaching event. The width of 20 m is reasonable based on photographic research and observations. The depth was measured at 4 m in August after the lagoon had closed. Several iterations of the momentum balance were computed using maximum and

minimum extremes values to test sensitivity since no actual measurements were taken during the various breach configurations and they vary in time as well (Figure 20).



Momentum balance calculated using different cross sectional areas of the inlet: average 20 m width 5 m depth (top), minimum 10 m width 3 m depth (middle), maximum 50 m width 20 m depth (bottom). Green lines indicate breaches and magenta lines indicate closures.

Figure 20. Three plots showing the sensitivity of the momentum balance.

Using the most reasonable parameters for the cross section of the inlet of 20 m width and 5 m depth, the results show the breaches occur when the total ocean forcing (tides and waves) are below the discharge and closure occurs when the ocean forcing is greater than the discharge. Using the minumum values of 10 m width and a 3 m depth similar results are seen showing tide and wave energy below the discharge equate to a breach and when it is above the discharge closure occurs. The only significant difference was using maximum width of 50 m and depth of 20 m which would indicate the offshore jet would be enorumous equal to that of a large river, which is unrealistic. Beach slope was taken into consideration and the calculations all used a slope of 1/10 which is the average for this beach. Different slopes were used from 1/25 which resulted in the wave energy being less and a steep slope of 1/5 which showed the wave energy being dramicatly higher. Both cases make sense, with a shallower slope wave energy would dissispate sooner due to the larger surfzone before reaching the beach and with a steeper slope, the waves would practially be breaking right on the beach and most of the energy would be dissipated and or reflected.

What the momentum balance shows is that in order for a breach to occur the discharge must increase but the ocean forcing has to remain the same or if the discharge does not change but the ocean forcing decreases than the river will breach. This is typically seen during dry winters when there is zero or very low discharge and an increase in wave energy, usually in December through February there may be a breach from overtopping alone but they are short in duration as the flow is not strong enough to erode the berm inlet significantly and the increased wave energy quickly fills the inlet back up. On the contrary during a wet winter, as was seen this year, when the discharge increases it will overcome the ocean forcing.

Using the same forcing but with typical "summer" conditions (wave heights = 1 m) a momentum balance was calculated (Figure 21). The mean discharge in December (1.01 m^3/s) was less than the mean discharge in June (1.5 m^3/s) but since the wave heights are typically smaller in the summer than the winter there was not enough ocean forcing to close the river.

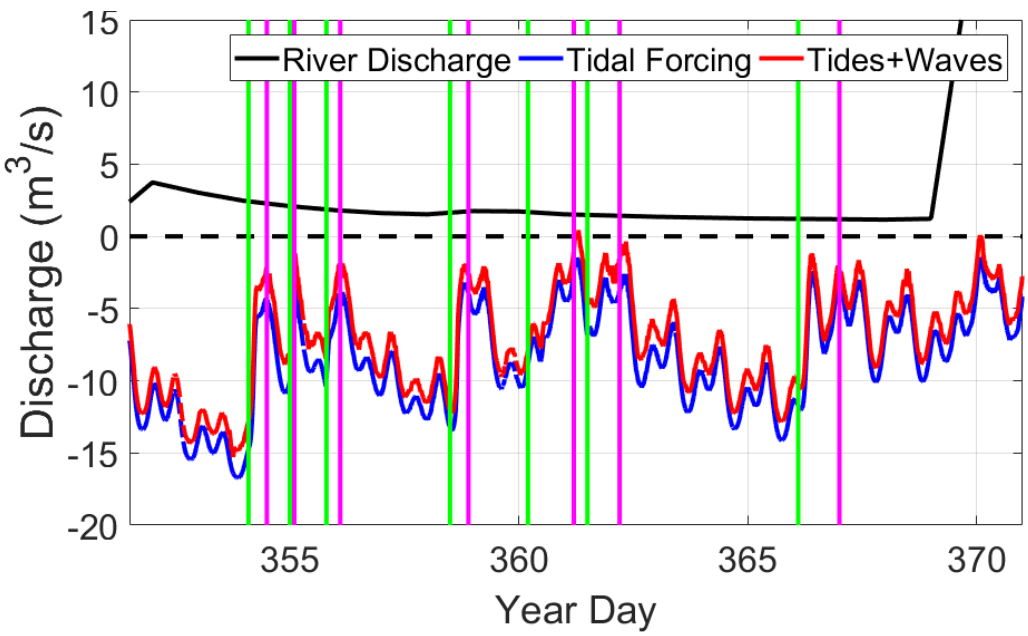


Figure 21. Momentum balance using wave heights of 1m, which is typical during the summer months. Green lines indicate breaches and magenta lines indicate closures for existing conditions.

C. PREDICTABILITY

Prediction of a breach or closure event is still a hard question to answer. A simplified model and has been developed (Battalio et al. 2006) but would need to be adapted and tested for a specific beach or one similar prior to running it which may be possible if there is enough lead time. During the rapid planning process, which is defined as 48 hours for the U.S. Navy that would not be practical and the computing power required not available. A Breach Susceptibility Index was developed by Kraus which looked at the height and width of the beach barrier, the elevation of run-up, the duration of the run-up, wave height and period, but this was for breaching from the seaward side (Kraus et al. 2002). It could be used in conjunction with other parameters that are routinely forecasted such as precipitation from which a discharge could be inferred, wave heights and tides. Of course, getting accurate measurements of actual beach dimensions could be difficult in semi-permissive and non-permissive environments but as technology continues to advance beach measurements could be obtained through the use of small UAVs and computer software. Predicting a closure may be easier since all of the

observed closure happened during a rising or high tide but the discharge, wave height and tides are still required. With further study, using a simple momentum balance prediction could be possible with a fair degree of accuracy.

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VII. CONCLUSION

Ephemeral rivers exist in all parts of the world, but due to their intermittent flow where they meet they ocean is dynamically challenging. Understanding the hydrodynamics of the river-ocean interface is a difficult subject. The objective of this study was to understand the processes that cause the Carmel River to periodically open and close by looking at a momentum balance. Changes in lagoon water levels are dominantly driven by discharge in determining when the river will remain open. Since the pressure gradient is always directed offshore, when that pressure gradient is balanced by wave and tidal forcing that leads to episodic openings and closures of the river inlet.

The lagoon water levels were observed from early November through January, and during an 18-day period, several fluctuations attributed to breaching were noticed. Since the lagoon water levels are always higher than the ocean, there is an offshore directed pressure gradient. When the water levels in the lagoon rise due to an increase in the discharge beyond to what the beach barrier can hold, a breach occurred. However, there they were short-lived, averaging only 6.5 hours and soon closed. An initial breach occurred after a rain event which increased the discharge to 3.7 m^3/s but slowly decreased over the next two weeks to minimum of 1.2 m^3/s. Utilizing a momentum balance when the ocean forcing (waves plus tides) increased the discharge was not sufficient to keep the inlet open. Only when the discharge increased higher than 5.5 m^3/s did the inlet remain open (James 2005). By analyzing water levels, wave heights and tides compared to the discharge we were able to determine that closures were attributed to ocean forcing which balanced the offshore pressure gradient. This was tested with the momentum balance by using the same discharge but decreasing the wave heights to 1 m, which is typical summer conditions, and the ocean forcing was not sufficient to close the inlet, as was observed through mid-summer as the inlet remained open.

A breach could not be correlated with the tide stage or wave height as they occurred during different stages of the tidal cycle and with different wave heights, but could be correlated to discharge. If discharge increases and the ocean forcing remains the same or if discharge remains the same and ocean forcing decreases, a breach will occur.

Closures were correlated to maxima in ocean forcing as they occurred during a rising or high tide and an increase in wave heights. If discharge is less than or equal to ocean forcing, then a closure will occur. The onshore directed ocean forcing acted against the discharge and was enough to fill the inlet.

LIST OF REFERENCES

Barnard, P., and J. A. Warrick, 2010: Dramatic beach and nearshore morphological changes due to extreme flooding at a wave-dominated river mouth. *Marine Geology*, **271,** 131–148.

Basco, D. R., and C. S. Shin, 1999: A one-dimensional numerical model for storm-breaching of barrier islands. *J. of Coastal Res.*, **15,** 241–260.

Battalio, B., D. Danmeier, and P. Williams, 2006: Predicting closure and breaching frequencies of small tidal inlets—A quantified conceptual model 2006: (In 5 Volumes) | World Scientific. *Coastal Engineering,* **1,** 3937–3949.

Behrens, D. K., F. A. Bombardelli, J. L. Largier, and E. Twohy, 2013: Episodic closure of the tidal inlet at the mouth of the Russian River—A small bar-built estuary in California. *Geomorphology*, **189,** 66–80.

Bertin, X., and M. Olabarrieta, 2016: Relevance of infragravity waves in a wave-dominated inlet. *J. Geophys. Res. Oceans*, **121,** 5418–5435.

Counts, C., 2016: Another year, another emergency—Sandbar breached to avert flooding. *The Carmel Pine Cone*, Carmel Communications, Inc., 2.

Davidson, M. A., B. D. Morris, and I. L. Turner, 2008: A Simple numerical model for inlet sedimentation at intermittently open-closed coastal lagoons. *Continental Shelf Res.*, **29,** 1975–1982.

Dean, R. G., and R. A. Dalrymple, 1991: *Water Wave Mechanics for Engineers and Scientists.* World Scientific Publishing Co. Pte. Ltd., 353 pp.

Feeney, M. B., and D. A. Gardner, 1989: Hydrogeologic investigation Carmel River aquifer coastal portion, 187 pp.

Hart, D. E., 2007: River-mouth lagoon dynamics on mixed sand and barrier coasts. *J. Coastal Res.***,** 927–931.

Herbers, T. H. C., S. Elgar, and R. Guza, 1995: Generation and propagation of infragravity waves. *J. Geophysical Res: Oceans*, **100(C12),** 24863–24872.

James, G. W., 2005: Surface water dynamics at the carmel river lagoon water years 1991 through 2005. M. P. W. M. Dirstict, Ed.

Komar, P. D., 1998: *Beach Processes and Sedimentation.* Second ed. Prentice-Hall, Inc., 544 pp.

Kraus, N. C., and S. Munger, 2008: Barrier beach breaching from the lagoon side, with reference to Northern California. *Shore & Beach*, **76,** 33–43.

Kraus, N. C., A. Militello, and G. Todoroff, 2002: Barrier breaching processes and barrier spit breach, Stone Lagoon, California. *Shore & Beach*, **70**.

Laudier, N. A., E. B. Thornton, and J. MacMahan, 2011: Measured and molded wave overtopping on a natural beach. *Coastal Engineering*, **58,** 815–825.

Malhadas, M. S., P. C. Leitão, A. Silva, and R. Neves, 2009: Effect of coastal waves on a sea level in Óbidos Lagoon, Portugal. *Continental Shelf Res.*, **29,** 1240–1250.

March, R., A., 2012: *River in Ruin—The Story of the Carmel River.* University of Nebraska Press, 192 pp.

Orescanin, M., B. Raubenheimer, and S. Elgar, 2014: Observations of wave effects on inlet circulation. *Continental Shelf Res.,* **82,** 37–42.

Ranasinghe, R., and C. Pattiaratchi, 2011: The seasonal closure of tidal inlets: Causes and effects. *Coastal Engineering*, **45,** 601–627.

Rich, A., and E. A. Keller, 2013: A Hydrologic and geomorphic model of estuary breaching and closure. *Geomorphology*, **191,** 64–74.

Thomas, R., L., 1996: Enhancing threatened salmonid populations: a better way. *Fisheries*, **21,** 12–14.

Thornton, E. B., and R. Guza, 1983: Transformation of wave height distribution. *J. Geophysical Res.: Oceans*, **88,** 2156–2202.

Wargula, A., B. Raubenheimer, and S. Elgar, 2014: Wave-driven along-channel subtidal flows in a well-mixed ocean inlet. *J. Geophysical Res.: Oceans*, **119,** 2987–3001.

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